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14. ABSTRACT
This is the final report for the IARPA CSQ project at Yale University, on the coherence limits of superconducting charge qubits. During this project, we performed the proposed work investigating the various sources of decoherence and their origins in different materials, using the “participation ratio” paradigm that we developed and disseminated in the community. The original project goal was to increase by an order of magnitude the coherence time of the state-of-the-art qubits (transmons and fluxonium designs) from a few microseconds to greater than 20

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Report Title

Final Report: Materials Limits on Coherence in Charge Qubits

ABSTRACT

This is the final report for the IARPA CSQ project at Yale University, on the coherence limits of superconducting charge qubits. During this project, we performed the proposed work investigating the various sources of decoherence and their origins in different materials, using the "participation ratio" paradigm that we developed and disseminated in the community. The original project goal was to increase by an order of magnitude the coherence time of the state-of-the-art qubits (transmons and fluxonium designs) from a few microseconds to greater than 20 microseconds. By project end, we realized qubit and cavity devices with times in excess of a millisecond, or an improvement by almost three orders of magnitude. These results, especially improved "3D" designs, have been widely adopted and successfully reproduced by many groups across the superconducting qubit community. At program end, we have an existence proof that qubits satisfying the quantum error correction threshold are possible with existing materials and fabrication techniques, leading to a growing belief that large-scale quantum computation with solid-state devices will eventually be realized.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
12/30/2014	37.00	C. Wang, Y. Y. Gao, I. M. Pop, U. Vool, C. Axline, T. Brecht, R. W. Heeres, L. Frunzio, M. H. Devoret, G. Catelani, L. I. Glazman, R. J. Schoelkopf. Measurement and control of quasiparticle dynamics in a superconducting qubit, Nature Communications, (12 2014): 0. doi: 10.1038/ncomms6836
12/30/2014	1.00	G. Catelani, L. I. Glazman, K. E. Nagaev. Effect of quasiparticles injection on the ac response of a superconductor, Physical Review B, (10 2010): 0. doi: 10.1103/PhysRevB.82.134502
12/30/2014	2.00	M H Devoret, R J Schoelkopf, S M Girvin. Circuit QED and engineering charge-based superconducting qubits, Physica Scripta, (12 2009): 0. doi: 10.1088/0031-8949/2009/T137/014012
12/30/2014	3.00	L. DiCarlo, M. D. Reed, L. Sun, B. R. Johnson, J. M. Chow, J. M. Gambetta, L. Frunzio, S. M. Girvin, M. H. Devoret, R. J. Schoelkopf. Preparation and measurement of three-qubit entanglement in a superconducting circuit, Nature, (09 2010): 0. doi: 10.1038/nature09416
12/30/2014	4.00	M. D. Reed, L. DiCarlo, B. R. Johnson, L. Sun, D. I. Schuster, L. Frunzio, R. J. Schoelkopf. High-Fidelity Readout in Circuit Quantum Electrodynamics Using the Jaynes-Cummings Nonlinearity, Physical Review Letters, (10 2010): 0. doi: 10.1103/PhysRevLett.105.173601
12/30/2014	5.00	Baleegh Abdo, Flavius Schackert, Michael Hatridge, Chad Rigetti, Michel Devoret. Josephson amplifier for qubit readout, Applied Physics Letters, (2011): 0. doi: 10.1063/1.3653473
12/30/2014	6.00	G. Catelani, J. Koch, L. Frunzio, R. J. Schoelkopf, M. H. Devoret, L. I. Glazman. Quasiparticle Relaxation of Superconducting Qubits in the Presence of Flux, Physical Review Letters, (02 2011): 0. doi: 10.1103/PhysRevLett.106.077002
12/30/2014	7.00	Archana Kamal, John Clarke, M. H. Devoret. Noiseless non-reciprocity in a parametric active device, Nature Physics, (01 2011): 0. doi: 10.1038/nphys1893
12/30/2014	8.00	G. Catelani, R. J. Schoelkopf, M. H. Devoret, L. I. Glazman. Relaxation and frequency shifts induced by quasiparticles in superconducting qubits, Physical Review B, (08 2011): 0. doi: 10.1103/PhysRevB.84.064517
12/30/2014	9.00	Archana Kamal, John Clarke, Michel H. Devoret. Gain, directionality, and noise in microwave SQUID amplifiers: Input-output approach, Physical Review B, (10 2012): 0. doi: 10.1103/PhysRevB.86.144510
12/30/2014	10.00	G. Catelani, S. E. Nigg, S. M. Girvin, R. J. Schoelkopf, L. I. Glazman. Decoherence of superconducting qubits caused by quasiparticle tunneling, Physical Review B, (11 2012): 0. doi: 10.1103/PhysRevB.86.184514
12/30/2014	11.00	Hanhee Paik, D. I. Schuster, Lev S. Bishop, G. Kirchmair, G. Catelani, A. P. Sears, B. R. Johnson, M. J. Reagor, L. Frunzio, L. I. Glazman, S. M. Girvin, M. H. Devoret, R. J. Schoelkopf. Observation of High Coherence in Josephson Junction Qubits Measured in a Three-Dimensional Circuit QED Architecture, Physical Review Letters, (12 2011): 0. doi: 10.1103/PhysRevLett.107.240501

12/30/2014 12.00 Vladimir E. Manucharyan, Nicholas A. Masluk, Archana Kamal, Jens Koch, Leonid I. Glazman, Michel H. Devoret. Evidence for coherent quantum phase slips across a Josephson junction array, Physical Review B, (01 2012): 0. doi: 10.1103/PhysRevB.85.024521

12/30/2014 13.00 Nicholas A. Masluk, Ioan M. Pop, Archana Kamal, Zlatko K. Minev, Michel H. Devoret. Microwave Characterization of Josephson Junction Arrays: Implementing a Low Loss Superinductance, Physical Review Letters, (09 2012): 0. doi: 10.1103/PhysRevLett.109.137002

12/30/2014 14.00 K. W. Murch, U. Vool, D. Zhou, S. J. Weber, S. M. Girvin, I. Siddiqi. Cavity-Assisted Quantum Bath Engineering, Physical Review Letters, (10 2012): 0. doi: 10.1103/PhysRevLett.109.183602

12/30/2014 15.00 K. W. Murch, E. Ginossar, S. J. Weber, R. Vijay, S. M. Girvin, I. Siddiqi. Quantum state sensitivity of an autoresonant superconducting circuit, Physical Review B, (12 2012): 0. doi: 10.1103/PhysRevB.86.220503

12/30/2014 16.00 A. P. Sears, A. Petrenko, G. Catelani, L. Sun, Hanhee Paik, G. Kirchmair, L. Frunzio, L. I. Glazman, S. M. Girvin, R. J. Schoelkopf. Photon shot noise dephasing in the strong-dispersive limit of circuit QED, Physical Review B, (11 2012): 0. doi: 10.1103/PhysRevB.86.180504

12/30/2014 17.00 K. Geerlings, S. Shankar, E. Edwards, L. Frunzio, R. J. Schoelkopf, M. H. Devoret. Improving the quality factor of microwave compact resonators by optimizing their geometrical parameters, Applied Physics Letters, (2012): 0. doi: 10.1063/1.4710520

12/30/2014 18.00 L. Sun, L. DiCarlo, M. D. Reed, G. Catelani, Lev S. Bishop, D. I. Schuster, B. R. Johnson, Ge A. Yang, L. Frunzio, L. Glazman, M. H. Devoret, R. J. Schoelkopf. Measurements of Quasiparticle Tunneling Dynamics in a Band-Gap-Engineered Transmon Qubit, Physical Review Letters, (06 2012): 0. doi: 10.1103/PhysRevLett.108.230509

12/30/2014 19.00 Simon E. Nigg, Hanhee Paik, Brian Vlastakis, Gerhard Kirchmair, S. Shankar, Luigi Frunzio, M. H. Devoret, R. J. Schoelkopf, S. M. Girvin. Black-Box Superconducting Circuit Quantization, Physical Review Letters, (06 2012): 0. doi: 10.1103/PhysRevLett.108.240502

12/30/2014 20.00 K. Geerlings, Z. Leghtas, I. Pop, S. Shankar, L. Frunzio, R. Schoelkopf, M. Mirrahimi, M. Devoret. Demonstrating a Driven Reset Protocol for a Superconducting Qubit, Physical Review Letters, (03 2013): 0. doi: 10.1103/PhysRevLett.110.120501

12/30/2014 21.00 Baleegh Abdo, Archana Kamal, Michel Devoret. Nondegenerate three-wave mixing with the Josephson ring modulator, Physical Review B, (01 2013): 0. doi: 10.1103/PhysRevB.87.014508

12/30/2014 22.00 Baleegh Abdo, Katrina Sliwa, Flavius Schackert, Nicolas Bergeal, Michael Hatridge, Luigi Frunzio, A. Douglas Stone, Michel Devoret. Full Coherent Frequency Conversion between Two Propagating Microwave Modes, Physical Review Letters, (04 2013): 0. doi: 10.1103/PhysRevLett.110.173902

12/30/2014 23.00 Matthew Reagor, Hanhee Paik, Gianluigi Catelani, Luyan Sun, Christopher Axline, Eric Holland, Ioan M. Pop, Nicholas A. Masluk, Teresa Brecht, Luigi Frunzio, Michel H. Devoret, Leonid Glazman, Robert J. Schoelkopf. Reaching 10 ms single photon lifetimes for superconducting aluminum cavities, Applied Physics Letters, (2013): 0. doi: 10.1063/1.4807015

12/30/2014 24.00 M. Hatridge, S. Shankar, M. Mirrahimi, F. Schackert, K. Geerlings, T. Brecht, K. M. Sliwa, B. Abdo, L. Frunzio, S. M. Girvin, R. J. Schoelkopf, M. H. Devoret. Quantum Back-Action of an Individual Variable-Strength Measurement, Science, (01 2013): 0. doi: 10.1126/science.1226897

12/30/2014 25.00 M. H. Devoret, R. J. Schoelkopf. Superconducting Circuits for Quantum Information: An Outlook, Science, (03 2013): 0. doi: 10.1126/science.1231930

12/30/2014 26.00 Flavius Schackert, Ananda Roy, Michael Hatridge, Michel H. Devoret, A. Douglas Stone. Three-Wave Mixing with Three Incoming Waves: Signal-Idler Coherent Attenuation and Gain Enhancement in a Parametric Amplifier,
Physical Review Letters, (08 2013): 0. doi: 10.1103/PhysRevLett.111.073903

12/30/2014 27.00 Baleegh Abdo, Katrina Sliwa, Luigi Frunzio, Michel Devoret. Directional Amplification with a Josephson Circuit,
Physical Review X, (07 2013): 0. doi: 10.1103/PhysRevX.3.031001

12/30/2014 28.00 Zaki Leghtas, Simon E. Nigg, Hanhee Paik, Eran Ginossar, Mazyar Mirrahimi, Luigi Frunzio, S. M. Girvin, R. J. Schoelkopf, Gerhard Kirchmair, Brian Vlastakis. Observation of quantum state collapse and revival due to the single-photon Kerr effect,
Nature, (03 2013): 0. doi: 10.1038/nature11902

12/30/2014 29.00 B. Vlastakis, G. Kirchmair, Z. Leghtas, S. E. Nigg, L. Frunzio, S. M. Girvin, M. Mirrahimi, M. H. Devoret, R. J. Schoelkopf. Deterministically Encoding Quantum Information Using 100-Photon Schrodinger Cat States,
Science, (09 2013): 0. doi: 10.1126/science.1243289

12/30/2014 30.00 Z. K. Minev, I. M. Pop, M. H. Devoret. Planar superconducting whispering gallery mode resonators,
Applied Physics Letters, (2013): 0. doi: 10.1063/1.4824201

12/30/2014 31.00 S. Shankar, M. Hatridge, Z. Leghtas, K. M. Sliwa, A. Narla, U. Vool, S. M. Girvin, L. Frunzio, M. Mirrahimi, M. H. Devoret. Autonomously stabilized entanglement between two superconducting quantum bits,
Nature, (11 2013): 0. doi: 10.1038/nature12802

12/30/2014 32.00 Kurtis Geerlings, Gianluigi Catelani, Robert J. Schoelkopf, Leonid I. Glazman, Michel H. Devoret, Ioan M. Pop. Coherent suppression of electromagnetic dissipation due to superconducting quasiparticles,
Nature, (04 2014): 0. doi: 10.1038/nature13017

12/30/2014 33.00 Baleegh Abdo, Katrina Sliwa, S. Shankar, Michael Hatridge, Luigi Frunzio, Robert Schoelkopf, Michel Devoret. Josephson Directional Amplifier for Quantum Measurement of Superconducting Circuits,
Physical Review Letters, (04 2014): 0. doi: 10.1103/PhysRevLett.112.167701

12/30/2014 34.00 Mazyar Mirrahimi, Zaki Leghtas, Victor V Albert, Steven Touzard, Robert J Schoelkopf, Liang Jiang, Michel H Devoret. Dynamically protected cat-qubits: a new paradigm for universal quantum computation,
New Journal of Physics, (04 2014): 0. doi: 10.1088/1367-2630/16/4/045014

12/30/2014 35.00 L. Sun, A. Petrenko, Z. Leghtas, B. Vlastakis, G. Kirchmair, K. M. Sliwa, A. Narla, M. Hatridge, S. Shankar, J. Blumoff, L. Frunzio, M. Mirrahimi, M. H. Devoret, R. J. Schoelkopf. Tracking photon jumps with repeated quantum non-demolition parity measurements,
Nature, (07 2014): 0. doi: 10.1038/nature13436

12/30/2014 36.00 U. Vool, I.?M. Pop, K. Sliwa, B. Abdo, C. Wang, T. Brecht, Y.?Y. Gao, S. Shankar, M. Hatridge, G. Catelani, M. Mirrahimi, L. Frunzio, R.?J. Schoelkopf, L.?I. Glazman, M.?H. Devoret. Non-Poissonian Quantum Jumps of a Fluxonium Qubit due to Quasiparticle Excitations,
Physical Review Letters, (12 2014): 0. doi: 10.1103/PhysRevLett.113.247001

TOTAL: **37**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 1.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Robert Schoelkopf:
IARPA Exceptional Contribution Award, 2011
John Stewart Bell Prize, 2013 (with M. Devoret)
Fritz London Memorial Prize, 2014 (with M. Devoret and J. Martinis)
Max Planck Forschungspreis (Max Planck Research Award), 2014
M. Devoret:
John Stewart Bell Prize, 2013 (with R. Schoelkopf)
Fritz London Memorial Prize, 2014 (with R. Schoelkopf and J. Martinis)
Matthew Reed (PhD Student at Yale, graduated 2013):
CGS/Proquest Distinguished Dissertation Award, 2014
APS Richard Greene Award for experimental condensed matter physics, 2014

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Vladimir Manucharyan	0.50	
Matthew Reagor	1.00	
Kurtis Geerlings	1.00	
Nick Masluk	0.50	
Archana Kamal	0.50	
Katrina Sliwa	0.70	
Eric Holland	1.00	
Andrei Petrenko	1.00	
Jacob Blumoff	0.50	
Kevin Chou	1.00	
Flavius Schackert	0.50	
Anirudh Narla	1.00	
Ankit Disa	0.20	
Adam Sears	0.50	
Chris Axline	1.00	
Zlatko Minev	1.00	
Kyle Serniak	0.30	
Uri Vool	0.30	
Evan Zalys	0.30	
Philip Reinhold	0.50	
FTE Equivalent:	**13.30**	
Total Number:	**20**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Luyan Sun	1.00
Hanhee Paik	1.00
Shyam Shankar	1.00
Baleegh Abdo	0.30
Gianluigi Catelani	1.00
Chen Wang	1.00
Ioan Pop	0.70
Zaki Leghtas	0.50
Nissim Ofek	0.50
FTE Equivalent:	**7.00**
Total Number:	**9**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Robert Schoelkopf	0.20	No
Michel Devoret	0.20	No
Luigi Frunzio	0.50	
Steven Girvin	0.20	Yes
Leonid Glazman	0.10	
Mazyar Mirrahimi	0.50	
FTE Equivalent:	**1.70**	
Total Number:	**6**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME	
Vladimir Manucharyan	
Adam Sears	
Archana Kamal	
Flavius Schackert	
Kurtis Geerlings	
Nick Masluk	
Total Number:	**6**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Technology Transfer

Investigating the Materials Limits on Coherence in Superconducting Charge Qubits

Final Report for IARPA CSQ Grant to Yale University

W911NF-09-1-0369

Michel Devoret

Luigi Frunzio

Steven Girvin

Leonid Glazman

Robert Schoelkopf

Yale University

Departments of Applied Physics and Physics

12/4/14

Report Abstract:

This is the final report for the IARPA CSQ project at Yale University, on the coherence limits of superconducting charge qubits. During this project, we performed the proposed work investigating the various sources of decoherence and their origins in different materials, using the "participation ratio" paradigm that we developed and disseminated in the community. The original project goal was to increase by an order of magnitude the coherence time of the state-of-the-art qubits (transmons and fluxonium designs) from a few microseconds to greater than 20 microseconds. By project end, we realized qubit and cavity devices with times in excess of a millisecond, or an improvement by almost three orders of magnitude. These results, especially improved "3D" designs, have been widely adopted and successfully reproduced by many groups across the superconducting qubit community. At program end, we have an existence proof that qubits satisfying the quantum error correction threshold are possible with existing materials and fabrication techniques, leading to a growing belief that large-scale quantum computation with solid-state devices will eventually be realized.

Period of performance
Sept 1, 2009-Aug 31, 2014

Project Overview:

This IARPA CSQ project was constructed to be a comprehensive theoretical and experimental investigation into the coherence time limits for state of the art superconducting qubits such as the transmon, the fluxonium, and also microwave cavities used in circuit QED experiments. Improving the coherence time of these solid-state devices for quantum information processing was one of the main challenges and unknowns regarding their ultimate potential as a quantum technology.

The project was a collaboration between two theoretical groups (Prof. Steve Girvin and Prof. Leonid Glazman) and two experimental groups (Prof. Rob Schoelkopf and Prof. Michel Devoret, as assisted by senior research scientist Luigi Frunzio), all located at Yale University. At the project outset our initial goal was to characterize our existing devices in order to divine which of the known or suspected sources of loss and decoherence were actually most important, to then pinpoint their location or the materials defects in which they originated, and then to design and fabricate devices with improved characteristics and materials so as to increase the coherence time. At the project outset, our coherence times were already the best in the world by approximately a factor of five, and throughout the project (and indeed over the last decade, continuously), our Yale team has held the record for best qubit lifetimes. Due to the work sponsored and performed under this project, the coherence times increased by more than two orders of magnitude, continuing the exponential advancements which we sometimes refer to as "Schoelkopf's Law." As summarized in Figure 1, this means we not only met the original project goals of improving lifetimes by a factor of ten, but we also exceeded our ***revised*** goals of improving by a further factor of ten.

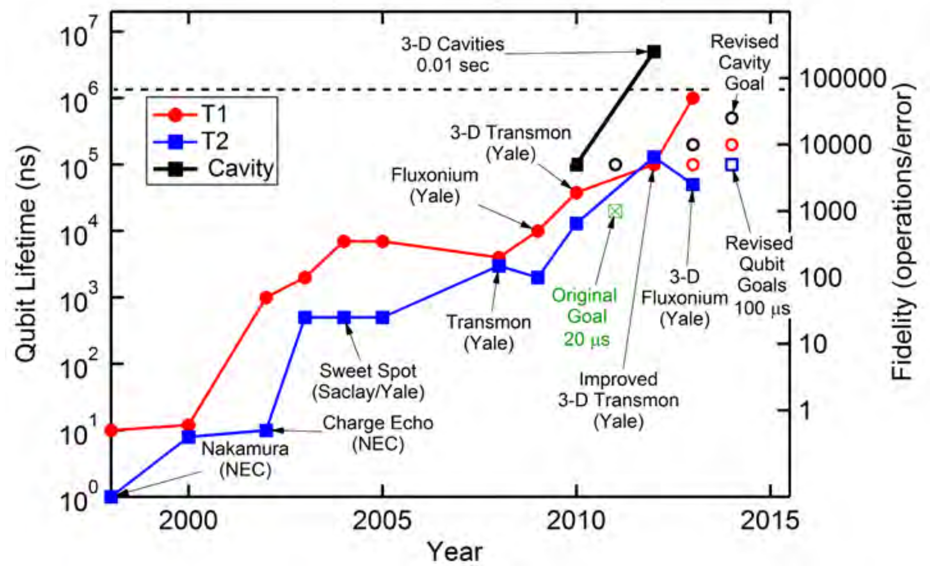

Figure 1: "Schoelkopf's Law" plot of best coherence for superconducting qubits and cavities versus year. The transmon qubit times as of ~ 2009, approximately 1-2 microseconds, were the state of art at the project's outset. The green box shows the original proposal goal to improve this performance by a factor of ten, to greater than 10 microseconds. The open red, blue, and black circles indicate the revised project goals for further improvements in T1, and T2 of qubits, and the coherence time of cavities, respectively. The additional solid points show that our results exceeded all of these goals before the project end.

The original project was composed of seven different subtasks, which will be briefly reviewed below, along with references to the corresponding publications. During the project a total of 37 publications referencing IARPA funding were accepted or appeared in print (one of these, has been accepted for Nature Communications but not yet appeared), including five papers in Nature (and one each in Nature Physics and Nature Communications), three in Science (including one invited review article on the status of superconducting quantum computing as of 2013, ref [13]), 14 papers in Physical Review Letters, and four in Applied Physics Letters. In addition, we applied for and received a supplemental funding increase in 2011, which was used for additional dilution refrigerators to increase our experimental throughput, and to allow three additional tasks – the characterization of the new 3D cavities, 3D transmons, and a comparison of decoherence mechanisms in fluxonium versus transmon qubits.

Task A, Theory of Mesoscopic Superconducting Systems:

This was a theory task, led by Prof. Leonid Glazman, was aimed at understanding the influence of quasiparticles and other mesoscopic effects in superconductors on the coherence of qubits and on losses in superconducting films, and comparing these to experiment. This task supported a postdoc, Gianluigi Catelani, who is now a group leader at Forschungszentrum Juelich in Germany, but continues to collaborate with our team at Yale. This collaboration will continue under a subcontract from Prof. Schoelkopf's Max Planck Prize funds. This task accomplished all of our goals, several theory papers were published elucidating new effects in superconductors, including references [28,30,32,36]. Furthermore, these theory predictions were then tested in actual qubits and cavities. These included the observation of the “cos ϕ” effect in fluxonium qubits (appeared in Nature, reference [6]), the observation of quasiparticle dynamics in both transmon and fluxonium qubits ([1,2,20]), a detailed fitting of the surface impedance for aluminum in the temperature dependence of 3D cavities [15], and studies of superinductances [26,], and the temperature dependence of frequency and lifetime of transmon qubits [27]. One interesting conclusion of these works is that a wide variety of qubits still suffer from anomalous (i.e. non-equilibrium populations) quasiparticles, but that through accidental and intentional quasiparticle trapping, these quasiparticles are not the sole contributor to current lifetime or quality factor limits. Work on further reducing these quasiparticles and their effects on coherence is ongoing today.

Task B, Modelling and Simulation of Circuits:

This was a second mainly theoretical task, headed by Prof. Steve Girvin, aimed at improving our understanding of the design and optimization of complex, multi-qubit circuits. In particular, we needed to further develop our control of the electromagnetic environment presented to our qubits, and ensure that spontaneous emission could be suppressed as a decoherence mechanism. This control was greatly improved by the introduction of “3D” device concepts, which have the major advantage that the device, the qubit chip, the sample package, and all electrical connections can be designed and modelled as a whole. To use these advantages, we created the “black box quantization” (or BBQ) theory of quantum circuits (Nigg et al., ref [19]). This technique, combined with careful computer modeling of the electromagnetics of the package, allows for first principles Hamiltonian design for circuits, where parameters can be designed and predicted to better than a few percent, limited mostly by fabrication tolerances (of junction critical currents, or Josephson energies, ~2%) and the machining and alignment tolerances of sample holders and chips, also about 1-2%. This represents a major advancement in control and prediction over earlier designs (even all-planar structures), and has greatly enabled all further experiments. This technique is now widely used in the community for all transmon related designs. Additional works on quantum circuit design include refs [21, 24, 25, 29, 37]. Another aspect of improved circuit design is the concept of participation ratio, which has been extensively employed in all of our other works, and described at numerous conferences. Though unpublished, this concept has also been widely adopted in the field.

Task C, Bulk Materials Characterization:

In this task, we devised new test structures and protocols to test the basic properties of bulk materials in the high-Q, quantum regime. One of the ideas proposed was to develop three-dimensional, ultra-high-Q ($Q > 10^7$) superconducting cavities, which could be used to determine the loss tangent of e.g. typical sapphire and silicon substrates before any device fabrication or processing. These techniques then developed into the full 3-D circuit QED architecture which has yielded both the best coherence times of cavities and qubits to date, and greatly informed our understanding of the current limits in superconducting quantum circuits.

We investigated a variety of different cavity designs (including rectangular and cylindrical “waveguide” cavities, and “coaxial” resonators consisting of a bulk machined quarter-wavelength stub), and obtained what are still the best quality factors and lifetimes for superconducting cavities in the quantum regime (with the possible exception of the Fabry-Perot resonators used by the Ecole Normale group of Serge Haroche in Rydberg-atom cavity QED). As reported in our Applied Physics Letter publication, (Reagor et al., [15]), our best results were obtained with high-purity (>99.999%) aluminum, after a simple chemical polishing step. We obtained Q factors of 0.6 billion (single-photon lifetimes of ~ 0.01 seconds) for a cylindrical cavity, and quality factors of 50-100 million (lifetimes > one millisecond) for several rectangular and coaxial designs. Moreover, we were able to quantitatively understand the behavior of Q and cavity frequency as a function of temperature, which showed good agreement with a detailed analysis of the Mattis-Bardeen theory (performed with G. Catelani and L. Glazman under the theory part of this proposal) and allowed us to measure the superconducting penetration depth of aluminum and other superconductors. Interestingly, because of the relatively low surface conductor participation of these cavities (i.e. the small kinetic inductance fraction), the bounds placed on the surface Q of the conductors (this is the ratio of imaginary to real parts of the complex surface impedance), we obtained bounds which were consistent with but not more stringent than those obtained in more conventional patterned circuits, such as compact resonators or stripline resonators. In recent experiments, we have produced multi-qubit and multi-cavity devices with cavity resonators having single-photon lifetimes in excess of a millisecond, with full quantum control and measurement. These are being employed in experiments on quantum error correction.

Incorporating different amounts of dielectric material into these cavities did not lead to a very good measurement of dielectric losses. Q factors were generally degraded by introducing such perturbations, but not in a way that was consistent with ANY single materials property. Our current belief is that perturbing a cavity in such a way produces asymmetries which can exacerbate radiation or losses due to imperfect seams and joints in a design. However, by incorporating transmon (and later fluxonium) qubits on a chip embedded in a 3D cavity, we obtained an approximately 100-fold increase in coherence times (a typical best time for T1 and T2 in these devices is between 100-200 microseconds), which will be discussed more below and has led to several new pieces of information about coherence in quantum circuits. In terms of bulk dielectric properties, it is actually these transmon results that now yield the best bounds. Because a 3D transmon stores greater than 95% of its dielectric energy in the bulk sapphire chip on which it is fabricated, the quality factor $Q = \omega T_1$ is basically the inverse of the bulk loss tangent. We therefore infer that the loss tangent of high purity sapphire is less than 10^{-6}. However, this cannot yet be ruled out as a significant contributor to current coherence limits. A less extensive set of measurements have been made with transmon qubits on high-resistivity Si wafers, with much less consistent results, but generally lower lifetimes and correspondingly less stringent loss tangent bounds. This work continues.

Task D, Reduce Capacitive Losses:

This task was aimed at measuring the dielectric losses in resonators and qubits, identifying where possible the material or location of these losses, and improving them. At the outset of the project there was a wide belief that dielectric losses due to thin surface layers (either on substrates, on the superconducting films themselves, or at the metal-substrate interfaces) was the main limitation on qubit lifetimes, which were then in the range of 1-2 microseconds. A study of planar devices (so-called "compact resonators" coupled to a CPW feed structure) made from niobium on sapphire was performed (Geerlings et al. [21]). These devices showed an improvement in Q with larger conductor separations (and therefore smaller "surface dielectric participation"), and also with an improved cleaning of the substrate before deposition, presumably improving the metal-substrate interface quality.

We also developed and tested the "vertical transmon" design, where the transmon capacitors are formed through the bulk thickness of the substrate (rather than through a thinner layer between two conductors on the same sided of the substrate, and therefore with more surface participation) and the 3D qubit design. Both of these designs showed improved coherence, which is consistent with the idea of reducing surface dielectric losses. More recently (and reported at the last IARPA review, but not yet published) we studied the coherence of a range of 3D designs which vary their geometry and the surface participation, but within the same wafer of fabrication and using all the same testing protocols.

This ability to vary surface participation (but controlling for example radiative losses) by almost two orders of magnitude has allowed us to make a much more detailed and convincing determination of the surface dielectric quality factor, which seems remarkably consistent across many different devices and fabrication styles. We are now employing this technique to quantify how improvements, such as different substrate cleaning or the deposition of “higher-quality” films using subtractive patterning (rather than the standard lift-off techniques) can still improve the performance of current devices. Interestingly, there is good evidence that even now, with coherences in the > 100 microsecond range, there may be approximately equal contributions from bulk dielectric, surface dielectric, and quasiparticle contributions. We are approximately in the same situation we were 4-5 years ago, albeit with over two orders of magnitude improvement in performance already in hand. The work on extending “Schoelkopf’s Law” continues, and the fact that coherence times have not yet saturated indicates that we have still not reached the ultimate physical limits for superconducting qubits and circuits. This is extremely encouraging for the future prospects of realizing useful quantum computation with this technology.

Task E, Scalable Fabrication of Qubits:

This was a relatively straight-forward task to investigate the yield and the spread of critical Josephson junction parameters, and to increase our fabrication capability to allow direct-write electron-beam lithography on four inch wafers. A new deposition machine (Plassys) capable of working with 4 inch wafers was purchased and installed, with lower background pressures than our existing machine. We successfully ported our fabrication process to this new machine, and measured the yield and critical current spread of junctions and qubits made with both this and our older system. We found that the spread in normal state resistances within a wafer was quite small (< 5%), and yields very high (about 98%, and perhaps higher), regardless of the deposition machine used or the background pressure conditions. This allows us to now fabricate a wafer and select out devices (based on room-temperature resistances and a scaling according to the Ambegoakar-Baratoff relation) with transmon qubit frequencies predictable at the 1-2% level. Moreover, we have made and tested nominally identical qubits from both deposition machines and found no differences in qubit coherence times. Our understanding and belief in the robustness of Josephson junction fabrication for qubits has been significantly enhanced.

Task F, Reduce Inductive Losses:

Since all resonators, cavities, and even Josephson qubits are essentially microwave L-C oscillators, we must consider both dielectric and conductor (or inductive) losses when trying to optimize and improve their quality factors and ultimately their coherence times. At the project outset, although it was suspected that dielectric loss was the leading or dominant factor (and in some works with low-quality deposited dielectrics, it was indeed the clear limitation), the importance of inductive losses, either in films and conductors or in the junctions (which are essentially nonlinear inductors) was not yet clear. In this project we have therefore undertaken studies of bulk conductor properties (or actually the real and imaginary parts of the surface impedance, as described in Task C above), as well as a variety of planar and other resonant structures. These include “compact resonators” (ref [21]), a new “whispering gallery” mode design based on a folded parallel plate transmission line (ref [8]), as well as “vertical” stripline resonators which use the full height of a single-crystal substrate. We succeeded in improving the quality factors of such resonators significantly (with whispering galleries and striplines, one can routinely obtain single-photon quality factors of a few million, i.e. lifetimes of 20-100 microseconds). These structures, as well as the fully three-dimensional resonators, have a wide range of kinetic inductance fractions, or conductor participation ratio. To compare results among different structures and materials, we use the “surface Q” or ratio of imaginary to real parts of the surface impedance. Bounds (lower limits) on the surface Q of niobium and aluminum films were obtained, in excess of several thousand. Interestingly, these are very similar to the bounds obtained with 3D cavities, because although their quality factors can be much higher, their surface participation is correspondingly much smaller. These results tend to indicate that conductor losses are not the dominant effect in for example transmon qubits, where the junction inductance strongly dominates. We have also investigated other materials (such as electroplated indium and aluminum) which yield similar results. Work on these phenomena continues, along with improved designs and packaging for planar, 3D, and hybrid resonant structures.

We were also able to put limits on the real part (i.e. the dissipation) of the impedance of Josephson junctions, and the dimensionless quantity which is the ratio of the imaginary impedance (the inductance) of a Josephson junction to its real part, which we termed the “Josephson quality factor” or Josephson Q. This property is one of the most crucial for the field, as it determines how long a coherence one can obtain while still benefitting from the necessary nonlinearity of the Josephson effect employed in all qubits. Surprisingly, and happily, we can now place extremely good limits on this performance factor of junctions. In a transmon qubit, for example, the dominant inductance (more than 95% of total) is made up by the inductance of the one or two small Josephson junctions. Therefore, the quality factor of a transmon places a direct bound on the quality factor of the junctions (this is only a bound, because one could for instance still be limited by dielectric loss even if the junction were perfect). Our current bounds are that the Josephson Q of small Dolan bridge aluminum JJ’s are in excess of several million. This also indicates that large-scale quantum computing with these Josephson junctions will eventually be possible.

The main mechanism that can give rise to a finite Josephson Q is the presence of non-equilibrium quasiparticles. Their tunneling across the junction can give rise to a dissipative term, as well as modifying the reactive part of the impedance. Again, under task A we developed a more complete theoretical description of the full impedance of a JJ, and tested this in several ways, with both transmon and fluxonium qubits. Recently, we have observed several new phenomena in quasiparticle dynamics, by studying the response of transmon and fluxonium qubits to intentionally generated excess quasiparticles (refs. [1,2,6,20. We have made quantitative measurements of the generation, recombination, and trapping rates of quasiparticles under the conditions of actual qubit operation, and observed the quantized trapping rate of quasiparticles by a single magnetic vortex penetrating an aluminum film. This work shows the surprising result that “standard” 3D transmons actually benefit significantly from the presence of trapped flux, which reduces quasiparticle densities and therefore qubit losses. This mechanism almost certainly accounts for most of the variability seen from run to run and laboratory to laboratory with these devices, and suggests some simple tricks which may further improve this mechanism and allow us to suppress quasiparticles as a source of qubit decoherence into the millisecond regime. Of course, further improvements will need to address all sources of decoherence, such as the dielectric losses mentioned above.

Task G, Perform Qubit Testing:

For all of the investigation under this project, we had to carry out a vast amount of cryogenic testing on the coherence of resonators, cavities, and qubits. During the grant period, we significantly expanded our laboratories and our testing capacity with the purchase, installation, and commissioning of multiple new “cryogen-free dilution” refrigerators. With enough effort, these have proven to be very reliable and capable machines.

The results of this testing program are of course seen in all of the experimental papers published (refs [1-3, 5-10, 14-18, 20-22, 25-27, 33-35]). This has led to a new understanding of some decoherence mechanisms. For instance, we were able to observe and quantitatively test the decoherence of transmon qubits due a “measurement-induced dephasing” or “photon-shot noise dephasing” induced by very small amounts of background radiation in circuit QED [22]. With improved filtering and control, this allowed us to improve the T2 times of 3D transmons to in excess of 100 microseconds (from the 10-20 microseconds in the initial experiments [27].

Finally, the improved coherence of devices and circuits, and the increased measurement capability of our lab, supported a large number of important physics experiments (refs[3, 5, 7, 9, 10, 11, 12, 14, 17, 18, 23, 33, 34, 35] directed at qubit control and entanglement, understanding the physics of measurement, and experiments towards quantum error correction with both traditional and new “cat-code” schemes using microwave cavities.

The following is the most recent interim technical report.

Aug 2014

We are now testing stripline resonators coupled to transmons in seamless sub-cutoff cylindrical waveguides. First preliminary results show: a) single photon quality factors of 5 million for the stripline resonators, which correspond to cavity lifetime of order 100 microseconds; b) qubit lifetimes of about 70 microseconds, which exceed those of vertical transmons. The similarity between these two lifetimes and the participation ratio of the modes suggests that losses may arise from the same source.

Technical Accomplishments This Period:

As reported in our presentations at the 2013 program review, we have met already all of our goals (including the increased coherence time goals inaugurated after our initial success) for qubit and cavity lifetimes. In addition, we have shown that properly designed and operated qubits and cavities can have coherence times for superpositions (T2 Ramsey or echo times) that are essentially limited by the finite energy losses (T1 processes). This means that we are emphasizing experiments to vary participation ratios and qubit designs in an attempt to localize the most important sources of these losses, which will be crucial for ***still further*** improvements of coherence. Despite the previous progress in coherence times and quality factors by two orders of magnitude or more, and the fact that this means our proposed materials quality metrics (see TOT table) have been met or exceeded, we find ourselves in a similar situation to the start of the project. Specifically, several candidate mechanisms, including surface dielectric quality, bulk dielectric loss, conductor losses, and quasiparticles are all possibilities whose influences need to be separated and individually investigated for the future beyond the lifetime of this IARPA project.

<u>Bulk materials properties:</u>

This task attempts to quantify the conductor losses of bulk superconductors and un-patterned thin films, as well as the dielectric loss of single crystal substrates.

Bulk conductor losses - Our paper on achieving single-photon cavity lifetimes approaching 0.01 seconds (Reagor et al) was published earlier this year. Interestingly, even this very high performance level (Q of nearly one billion, with participation ratio of about 10^{-5}) was not as high as one might have expected. For instance, our limit on surface Q for aluminum films from compact resonators, which have a Q of a few times 10^5 and a conductor participation ratio of few percent, suggest a bound on the conductor surface quality factor (Q_s) of about 10,000. If this were the only mechanism limiting 3D cavities, this would imply that we should have seen cavity Q's of several billion. Put another way, even the excellent Q factors of our 3D cavities do not yet place the most stringent bound on conductor loss. An interesting, if counter-intuitive, potential conclusion is that the surface properties of ultrapure (5N), chemically etched aluminum (with grain sizes visible to the naked eye!) are not as good as that of less pure, polycrystalline, sputtered or evaporated Al films. A second possibility (see below) is of course that these 3D cavities are limited by another process, such as magnetic fields. We have begun measurement of cavity and qubit lifetimes as a function of an applied magnetic field during cool-down, to place limits on the importance of trapped flux. This has also required a much more detailed investigation of magnetic shielding, and shed light on several difficulties (previously unappreciated in the field) in obtaining true zero field environments for optimal circuit performance.

In order to broaden our understanding of film losses in different materials, we have begun collaboration with the University of Chicago (Prof. David Schuster, a former student & postdoc from our team) and the superconducting technology group at Fermilab (led by Dr. Lance Cooley). We have shared our 3D designs with them, and have fabricated cavities in both ultrapure Niobium and Aluminum. Cavities are tested both in our lab and Prof. Schuster's, with funding for the Fermilab and Chicago efforts coming from other sources. The goal is to take advantage of the facilities and knowledge of Fermilab, which can perform, for example, electron-beam welding, highly controlled chemical etching, cleaning, and vacuum annealing of materials. The basic idea is to see if the accelerator cavity community, which regularly reports quality factors in the range of 10^{11} to 10^{12} (of course at very powers that are many, many orders of magnitude above the quantum domain), can teach us anything about materials properties. One of the main goals is also to realize a test-bed for very sensitive measurements of film losses, by developing a cavity geometry with ultra-high Q factors where we can replace one wall with a material or thin film that can be made with various technologies.

We have been through several rounds of fabrication, processing, and testing. We started with simple welded but un-etched cavities, adding cleaning and then annealing as subsequent steps with Q factor testing (compared between the two labs) in between. While these results are still in progress, we have not yet seen significant improvements in cavity Q over our standard designs. The best results so far are "only" Q ~ 50 million, or lifetimes of about one millisecond.

Bulk dielectric losses - Our best limit on these losses is still provided by the lifetimes of 3D transmons. The fact that these devices have >90% participation in the sapphire, and observed Q's of several million, places a limit of less than about 1e-6 on the loss tangent. We are using 3D cavities, whose Q's can be much better, to see if we can place a more stringent limit, which could rule this contributor in or out for the present qubit limits. In these cavity experiments, we find that the addition of dielectric material typically lowers the Q of a cavity by a factor of two to five. However, the observed losses do not seem to scale with either the participation ratio (amount of dielectric) or with ANY consistent value of dielectric loss tangent. This either indicates that materials properties are variable (perhaps due to processing or geometric variations such as wafer dicing), or that the actual mechanism of loss is due to a breaking of symmetries and perhaps anomalous output coupling (i.e. an analog of the Purcell effect). We are undertaking experiments in coaxial resonators to attempt to shed light on this issue.

<u>Film properties:</u>

As reported earlier this year, whispering gallery modes with frequencies around 3 GHz in resonators made of two superimposed sapphire wafers with thin-film Al rings patterned on them have been observed and their quality factors have been measured in the range 1-3 million. Based on these measurements, surface resistance of e-beam evaporated Al patterned films were estimated having quality factors in excess of 15,000.

In another attempt to quantify film losses, we have been testing cavities fabricated from a variety of different superconducting materials. For instance, in order to simplify the construction of 3D systems and reduce the time and cost of fabrication, we have had copper cavity forms electroplated (commercially) with both aluminum and indium. Despite the fact that one might expect much lower purity and crystalline quality in these materials compared to e.g. our Al or Nb cavities, they have rapidly shown single-photon quality factors in the range approaching 100 million (or one millisecond lifetime). Another interesting feature of the indium films is that they can allow devices to be assembled by cold-welding. This is a simple process involving a mild chemical cleaning just before pressing to assemble. We have evidence that this leads to a very high quality superconducting joint, and may remove some of the potential degradation of circuits due to joints and seams.

Capacitive losses:

One argument for the observed improvement of lifetimes in 3D transmons is that the geometry reduces the surface dielectric loss participation, which was believed and is believed to be the limiting source of T1 in planar designs. While calculations of this participation can be simply and accurately made for structures like cavities, qubits are generally more challenging. For instance, qubits are made with thin films that have rough edges and sharp corners, and the two conductors must closely approach and then touch each other to form the Josephson junction. We have been undertaking more detailed calculations using our participation ratio analysis and introducing the concept of effective parallel plate distance (EPPD), we have been investigating the importance of surface dielectric losses to resonator and qubit lifetimes. We find that our Yale results so far may be consistent with a single surface quality factor, indicating that this mechanism could still be a significant contributor to the lifetime of our current state of the art qubits. We are therefore beginning work on implementing qubits and resonators using surface preparations (such as either high-temperature deposited Al) or materials (such as TiN), which have recently been claimed by other teams to have a higher surface quality factor. Testing these materials with our qubit designs should allow for a definitive determination of the loss properties of these materials, or yield a further improvement of lifetimes. In combination with studies of the magnetic field sensitivity of transmon qubits, however, they point to a more complicated phenomenology than previously appreciated, or to the possibility that this mechanism may be associated in some way with quasiparticles and magnetic vortices in films.

Inductive losses:

Our recent activity in this area has focused on the study of quasiparticle dissipation in superconducting qubits. We use the fluxonium qubit biased near half-flux-quantum, since this is the point where quasiparticle dissipation is most sensitive to flux, and we can therefore distinguish it to dissipation due to other sources. We have set up an experiment combining a 3D fluxonium qubit having a relaxation time of about 1 millisecond at half-flux-quantum with a JPC phase preserving paramp. We have been able to follow the quantum jumps of the fluxonium qubits with a micro-second time resolution. This has allowed us to show that the statistics of the jumps are not Poissonian, showing that T1 itself fluctuates as a function of time. However, these fluctuations in T1 are well explained by a model in which the quasiparticle number on the island of the device fluctuates as function of time and does not average out over any timescale, from milliseconds to hours. This time scale is much longer than any intrinsic process associated with the superconductor, suggesting a source for QP excitations external to our sample.

In parallel, we are also improving setups to measure jumps in two separate qubits. This will allow the measurement of spatial as well as temporal correlations. Such refined correlation measurements should shed light on the possible origin of quasiparticles, and perhaps confirm the hypothesis that they may come from natural background radiation.

<u>Testing of improved qubits:</u>

We have analyzed measurements of decoherence times in presence of magnetic fields in different design transmon qubits. We show that vortices can improve the performance of superconducting qubits by reducing the lifetimes of quasiparticles excitations. Using a contactless injection technique with unprecedented dynamic range, we directly demonstrate the power-law decay characteristics of the quasiparticle recombination process, and show quantization of quasiparticle trapping rate due to individual vortices. We measure a “trapping power” of 6.0 μm2/μs for a single vortex, enough to dominate over the vanishingly weak recombination in a modern qubit.

We are continuing our testing of more designs for vertical transmons and multi-qubit devices to employ the improved coherence times. The recent goals have been to understand quantitatively the higher-order terms in the device Hamiltonian, and the contributions of the Purcell effect (see below).

We are also testing new designs for stripline resonators with improved packaging, which have some encouraging initial results.

Finally, to test the idea that anomalous losses may arise from complicated circuits and the role of seams in determining the cavity quality factor in 3D circuits, we have designed and tested several more compact 3D coaxial resonators, and qubits coupled to single and double seamless coaxial cavities (storage and read-out). These devices can be fabricated from a single block of high-purity superconductor, without any seams or openings that are not below a waveguide cutoff frequency and therefore exponentially suppressed. In this system, once reverse Purcell effect was reduced by decreasing qubit-storage cavity coupling, cavity lifetimes of 1.8 ms, an improvement of about a factor of 20 over our previous devices, and qubit coherence times of 12 microseconds have been observed. These coaxial resonators also place some of our most stringent bounds on conductor properties. Experiments are underway to demonstrate Ramsey lifetimes (to place limits on dephasing mechanisms) and to use these as a passive quantum memory.

<u>Fabrication and scaling:</u>

This task continues, and of course we continue to produce devices needed for all the projects in our foundry. As we have met most of our explicit goals for reproducibility and junction quality, we are focusing instead on characterizing the sources of loss.

<u>Circuit and electromagnetic simulation:</u>

This task is ongoing, and making steady progress. Members of the team made a two day trip to the offices of Ansoft HFSS (the manufacturer of our main finite-element calculation software) and developed refinements in accuracy and improvements in speed of our finite element simulations. We have also rewritten code for calculating multi-qubit and multi-cavity Hamiltonians from our Black Box Quantization theoretical model. These simulations are used in two crucial ways. First, we rely on them to calculate the effects of the generalized Purcell effect (i.e. the amount of dissipation inherited by a qubit or mode from its couplings to other modes, including readout channels, with finite Q) and higher-order nonlinearities. This is important for scaling to more complicated circuits, and a requirement for accurate characterization of the decoherence budgets of qubits. We are in the process of quantitatively testing these calculations against multi-mode devices of several different designs. Second, these calculations are employed for quantitative estimations of participation ratios of different materials components in qubits and cavities, used in the work described above.

Significant Changes to Technical Approach to Date:

None.

37 Published or Submitted Papers:

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ISSUES OR CONCERNS:

None.